A STUDY OF THE EFFECT OF THICKNESS ON FATIGUE STRENGTH OF 24S-T3 ALUMINUM ALLOY SHEET

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SUMMARY

A study of the variation of fatigue stress with four gages of 24S-T3 aluminum alloy sheet is presented in this investigation. Four sizes of aluminum alloy sheet; .032, .040, .064, and .072 inches thick were subjected to completely reversed bending stresses parallel to the grain, by a Sonntag Flexure Fatigue Testing Machine. The investigation was made in the stress range of 18,000 to 48,000 pounds per square inch. Tensile tests were made on specimens taken from the same sheet from which fatigue specimens were made to account for the variation in the physical properties. Data, results and conclusions of other investigations are included herein for comparison.

It should be borne in mind that the data recorded in this investigation is obtained from tests on samples taken from very few sheets of material. However, the properties of yield point, ultimate strength and percent elongation are noted to type the material and it is believed that the results obtained are typical for this material, for the thickness range investigated.

INTRODUCTION

For some time the effect of size on fatigue strength in the testing of steel specimens has been noted and more recently investigations have been carried on to determine the magnitude of this effect on the lighter alloys. Bond[1], in his "Fatigue Studies with Various Surface Conditions" was aware that while his results showed the fatigue strength for various surface conditions on .040 inch 24S-T his tests were directly limited to that alloy and only to that thickness of material. He recommended that further investigation be made on size effect to determine the variation of fatigue strength in the range of sheet thickness in use in fabrication of modern aircraft.

Only one phase of the suggested project is undertaken here. This phase is that of size effect of specimens with a polished surface condition, stressed in bending parallel to the directinn of rolling.

In a survey of the literature on the subject two articles in particular were noted which were later helpful in explaining the phencmenom brought out in the testing. Summaries of these articles; one by W. Buchmann[2] and the other by H. A. v Philipp[3] are included

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[1]Bond, A. C., "Fatigue Studies of 24S-T and 24S-T Alclad Sheet with Various Surface Conditions," A thesis. Georgia Institute of Technology, Atlanta, Ga. 1948.

[2]Buchmann, W., "Influence of Cross-Sectional Area on Fatigue Strength," Engineer's Digest, March 1945, pp. 136-137

[3]v.Philipp, H. A., "The Influence of Scale Effect and Cross Section Form on Fatigue Strength with Unequally Distributed Stress. Forschung. Ing. Wes., Volumme 13, 1942, pp. 99-111.

herein to give the more advanced ideas on the subject of size effect.

Buchmann investigated three light alloys Mg-Al6 ("Elektron AZM"), GMg-Al ("Elektron A9V"), and Al-Cu-Mg ("Igedur 26") with respect to size effect with the following results:

(a) There was a pronounced drop in flexural fatigue strength with increasing size, especially in the range of small cross-section dimensions (5 to 15 mm. dia.).

(b) Beyond a certain limit (30 mm. dia.) the rate of drop in the curves of flexural fatigue strength versus thickness is only slight; the curves tended asymptotically toward the fatigue strength due to reversed axial loads. The excess strength on reversed flexure over the asymptotic value is explained by the stabilizing effect of the slightly stressed inner fibers on the highly stressed outer fibers. This effect obviously depends on the stress gradient.

(c) The fatigue strength of unnotched samples due to reversed axial loads is independent of scale factor. With a notched sample, however, there is a stress gradient and consequently, due to the stabilizing effect there is an influence of size on the fatigue strength.

(d) With fatigue due to alternating torsion there is a distinct influence of the size of the test samples, even when unnotched.

A theoretical treatment of the problem of scale factor was undertaken by H. A. v. Philipp. His assumptions were based on a straight line stress distribution in flexural specimens up to a "stabilized layer." This stabilized layer extends from the outer fiber toward the neutral axis, its thickness depending on the cross section shape of the material, and the type of loading.

This simplified distribution assumed by v. Philipp for various thicknesses of specimens is shown in Figure 2 of Appendix III. This shows the stress in the stabilized layer (s) assumed constant. The stress as ordinarily computed by the $\frac{Mc}{I}$ equation is shown as a dashed line, while the shaded areas indicate the distribution assumed. With very thick specimens, of the order of 2 inches thick, there is very little difference between the $\frac{Mc}{I}$ distribution and that assumed here. Also, curves of axial and flexural fatigue versus size have very nearly the same value, the flexural fatigue curve having approached the more constant axial fatigue curve as an asymptote. The stress in the outer fibers of a large bar in flexure is very nearly the same as the stress in an unnotched axial loaded bar. With very thin specimens, of the order of 5 mm. or less, the stress distribution assumed approaches the third case of Figure 2 of Appendix III. The $\frac{Mc}{I}$ dashed line stress distribution is much in excess of the distribution of constant compressive stress and constant tensile stress at the outer fiber as shown by the shaded areas. Therefore, with thin specimens, the flexural fatigue life should be much longer than a specimen axially loaded to the same stress as the $\frac{Mc}{I}$ value, since the $\frac{Mc}{I}$ value does not actually develop. If we assume that the thin specimen having a shaded area stress distribution, fails at the same fatigue stress as the axial loaded specimens, we then have a basis for computation of flexural fatigue stress in terms of axial fatigue strength. This is illustrated in Appendix I.

Dr. v. Philipp proposes the above as a working hypothesis and sets forth a method for calculating the fatigue stress of various sizes, shapes, and working materials. One very interesting conclusion he arrived at is that the upper limit of flexural fatigue strength is reached when the height of the cross section is 6mm. for light alloys and about 20mm. for steel. In testing of flexural fatigue specimens Buchmann found that the fatigue strength did not increase infinitely with a decrease of size. At a thickness of specimen of 20 mm. for steel and 6 mm. for light metals the stress distribution of the thin specimen of Figure 2 was evidently approximated. Further decrease in sizes of test specimens below the above mentioned values could not change the distribution and hence there is no further departure from the $\frac{Mc}{I}$ equation with further decrease of size and the fatigue strength remains more constant.

The specimens tested in this investigation were all of the order of 1.25 to 2.75 mm. height of cross section. v. Philipp specifies that the stabilized layer for steel is 3.1 mm. thick and for aluminum is 1 mm. With v. Philipp's conclusion in mind this means that the tests conducted in this investigation may show very little variation of fatigue strength in that the stabilizing effect will have already reached a maximum with specimens thicker than those tested here.

MATERIAL

The material used in this investigation was 24S-T3 aluminum alloy sheet. Four sizes of sheet were tested: .032, .040, .064, and .072 inches thick. The investigation was held to these four sizes because the testing machine would require another type of specimen in order to test a heavier or lighter gage at the desired stress. Buchmann has pointed out that fatigue strength will vary with the shape of cross section tested, and as all specimens used in this investigation were constant strength beams of rectangular cross section, variation in data from this source was eliminated. One physical parameter only was intentionally varied, that is, the thickness or height of the specimen. It will be shown that other parameters, namely, yield point strength and ultimate strength also varied.

The physical properties of yield point stress, ultimate stress, and modulus of elasticity are presented in Table I of Appendix II. These are average values resulting from three tensile tests conducted on each of the four sheets of material. The .072 inch thick sheet showed the highest yield point and ultimate strength. The .064 inch thick sheet also showed larger values than those of the two thinner sheets. The .032 inch thick sheet and the .040 inch thick sheet showed yeild point stresses of nearly the same value while the ultimate strength of the .040 inch thick material was 1000 psi. higher that that of the .032 inch thick sheet. This variation may possibly be attributed to different amounts of cold working after heat treatment. Davis[4], Troxell and Wiskocil have noted that there is no direct relationship between endurance limit and other physical properties that will apply to all metals. Ultimate strength, elastic strength and ductility seem to influence the fatigue strength. It is not safe to assume that heat treatments which increase the static strength of an alloy increase the fatigue properties in porportion. The data obtained in this investigation is therefore adjusted for the variation in physical properties as shown later. Ductility was not considered as a parameter affecting the fatigue strength since its variation from sheet to sheet was relatively small.

The specimens used for the tensile tests were the standard American Society of Testing Materials Tension Test Specimen as described by Davis[4] in his handbook on materials testing. The tests were conducted on a Riehle Universal Hydraulic Testing Machine, a Huggenberger type extensometer being used to measure the elongations.

THE FATIGUE TESTING MACHINE

The tests described herein were run on a Sonntag Flexure Fatigue Machine, Model SF-2, with a capacity varying from a possible maximum of 250,000 pounds per square inch on .025 inch thick sheet

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[4] Davis, H. E., Troxell, G. E., and Wiskocil, C. T., The Testing and Inspection of Engineering Materials, McGraw Hill Book Co., 1941, p. 80, Fig. 48, Type B.

to a maximum of 20,000 pounds per square inch on .250 inch thick sheet. The motive power is produced by a $\frac{1}{4}$ horsepower synchronous motor operating at a constant speed of 1800 revolutions per minute. Three photographs, Figures 14, 15, and 16 show a sample loaded in the machine and indicate clearly the main features of loading. In the following discussion on the operation of the machine these photographs will be referred to in the description of the various components.

The Sonntag Machine applies a completely reversed load to the specimen. The amplitude of the applied load is independent of the amplitude of the deflection and hence of changes in deflection which might occur during the test run due to changes in internal crystalline structure or other properties of the test specimen. By adjusting the eccentricity of the mass the force output may be read directly from from the scale, B. The force is transmitted through rod, C, to load yoke, D. The travel of rod, C, is limited to the vertical, the side forces of the eccentric being eliminated by the pivot rod, E. The specimen is clamped in the load yoke by means of the pivot bar, F, clamp bar, G, and clamping bolts, H. The fixed end of the specimen is rigidly held in the pedestal, I, and clamped by bar, J, and bolts, K. Pedestal, I, is adjustable for different length specimens.

The machine is equipped with a micro-switch, L, which automatically shuts off the motor when the specimen breaks. Also it is provided with a counter, M, which registers the number of cycles to failure in a ratio of 1000:1.

As previously noted the force is applied by a rotating eccentric mass and remains a constant for any fixed value of the mass eccentricity. A system of inertia compensation is used in order to maintain the force applied on the specimen constant irrespective of amplitude. This means of compensation absorbs all the inertia forces in the vibrating system so that the eccentric force alone acts on the specimen. A mathematical proof of the method is presented in the operating manual of the machine.[5] However, stated simply, this method is as follows: A spring, the tapered drive shaft, N, is used whose deflection constant is equal to the inertia forces of the vibrating system. As the deflection of the system increases the inertia forces in turn increase, but compensating this is the spring reaction which cancels the inertia forces. This leaves only the eccentric force or a repeated force of constant maximum value applied on the specimen. Since the system must be in resonance for the condition to hold, it is only valid for a given frequency and a given mass system. The synchronous motor, O, maintains constant frequency for the system and the variable poise weights, P, are provided in order to adjust for differences in the mass of the system when different weight specimens are used.

As was noted in the foregoing paragraph the mass of the system must be kept constant and for this reason it was necessary to calculate the poise setting for each sheet of different thickness

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[5]Anonymous, "Instruction for Installation, Operation and Maintenance of Flexure Fatigue Testing Machine, Model SF-2, Serial No. 472875." Manual furnished by Sonntag Scientific Co., Greenwich, Connecticut, prepared July 1947, App. Print No. 90273-S

in order that the machine be tuned to resonance. Using the calculated effective weight of the specimen,

$$We = .385dt$$ [6]

where We = effective weight in pounds

d = density in pounds per cubic inch

and t = thickness of material in inches

and referring this to graph No. 90452-S [7] the poise setting for a particular specimen was determined. Graph No. 90452-S is a curve which was determined at the factory for the purpose of tuning this particular machine to resonance when using various thicknesses of material.

The last adjustment is that for the amount of force to be applied to give any desired stress. Graph No. 90446-S [8] is provided as a calibration curve of specimen stress per pound of force developed by the eccentric mass, against the thickness of the material. This curve is merely the adaptation of the familiar beam formula,

$$f = \frac{M\,y}{I}$$ [9]

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[6] Ibid., p. 90450-S, sheet 3.

[7] Ibid., graph No. 90452-S.

[8] Ibid., graph No. 90446-S.

[9] Niles, A. S., and Newell, J. S., Airplane Structures, Second Edition, Vol. 1 (New York: John Wiley and Sons, Inc., 1938) p. 143

where f = unit normal stress in psi.

M = bending moment on the cross-section in in.-lbs.

I = moment of inertia of section about its neutral axis in inches ^{4}

y = distance parallel to the plane of bending between the point under consideration and the neutral axis, or one half the thickness in inches for maximum stress, which occurs at the surface.

This formula may be modified to include the force of the eccentric mass and may be written

$$f = \frac{P\,l\,y}{I}$$

where $P \times l = M$

P = force of the eccentric mass in lbs.

l = the distance in inches from the load yoke to the point in question on the test section of the specimen.

The graph was found to be very useful in that it eliminated the making of individual calculations for each specimen each time the load was varied. Knowing the desired stress, it was only necessary to read the specimen stress per pound of force for a given thickness from the graph and divide this value into the desired stress for the machine setting on the eccentric.

Important considerations in running any specimen include: (1) adjusting and determining the values of the loads to be applied, and (2) determining the weakest section or point of minimum thickness.

THE FATIGUE SPECIMENS

A planform of the specimens used for the fatigue tests are shown in Figure 1, giving complete dimensions and mounting details. As may be deduced from the layout of the specimen of Figure 1, it incorporated a beam with constant bending stress as the cross section. Since the bending stress is constant in the section of the beam between the end radii the break may be expected to occur at any section between the radii. Figure 17 bears out this expectation showing that the specimens broke at random locations in the test section.

Preparation: In preparing the specimens it was necessary at all times during the handling of the material to be extremely careful not to scratch or mar the specimen. In order to insure that the planform be maintained identical for the specimens originally planned on, two jigs were used in the making of the specimens of Figure 17. The drill jig as shown in Figure 18 maintains uniformly accurate location of the holes which maintain a constant distance between the pedestal and the load yoke. A template of the planform was made of $\frac{1}{4}$ inch tool steel into which guide pins were mounted. These pins were located so as to slip through the holes in the specimen previously made by the drill jig. A high speed router guided by the template was then used to cut the specimens to uniform planform shape. The tool marks in the edges were removed with No. 240 Aloxite Finishing Cloth, and the edges were then polished with crocus cloth. The specimens were then buffed on a cloth polishing wheel using a fine polishing compound. Care was taken during the polishing that the sample did not heat up to more than handling temperature. All specimens were carefully inspected for nicks or scratches on the surfaces and finished edges.

The thickness of each specimen was checked with a micrometer, but very little variation in thickness was noted of specimens cut from the same sheet. It was noted however that sheets of the same basic gage thickness may vary up to .0015 inches from sheet to sheet.

Grain Direction: All specimens were cut with the centerline parallel to the direction of rolling of the sheet in order to give uniformity of this parameter and to allow for a longer life of the tests. Brick and Phillips[10] have investigated the effect of grain direction on 24S-T and arrived at the following conclusions: At 5×10^8 cycles for 24S-T samples cut parallel to the direction of rolling a value of 20,500 ± 1000 psi. was indicated and for samples cut perpendicular to the direction of rolling a value of 18,500 ± 2000 psi. was indicated. The direction of bending parallel to the direction of rolling was selected for investigation as it was necessary to limit the study to only one grain direction.

TEST PROCEDURE

The specimen is clamped in the machine with the centerline of the specimen perpendicular to the face of the pedestal. The

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10 Brick, R. M., and Phillips, A., "Fatigue and Damping Studies of Aircraft Sheet Materials:" Transactions, American Society for Metals, 29:441, June 1941

yoke is then clamped to the extended ends of the specimen. The poise weights are set to a distance from the poise weight pivot dependent on the thickness of the specimen. The stress at which the specimen is to be tested is chosen and the eccentric weight is set accordingly. The counter is set to zero and the test may then begin.

The tests were usually started at the high values of stress and run to the lower values, as this method allows the curve of fatigue stress versus number of cycles to be estimated as the testing proceeds. This method made it possible to estimate the length of time required for the specimen to break. Almost all the tests were continued to failure except for some few specimens which had not failed after 10 or 15 million cycles of stress. In such cases the machine was stopped to shorten the time required for the test program. Such points are located on the plots with the conventional horizontal arrows at the points where the tests were discontinued.

DISCUSSION OF RESULTS

The results of this investigation are presented in the form of curves of fatigue strength versus cycles to failure, Figures 3 through 9. Figures 3 through 6 show the conventional curves of Fatigue Strength versus Cycles to Failure for the four sizes of sheet tested. These curves show the range of scatter of the data which is comparable to that found in other reports on the subject of fatigue. The fatigue curve for the material of .072 inch thickness, Figure 6, extends only to a fatigue stress of 35,000 psi. as this was the upper limit of the stress obtainable from this machine on this thickness of material.

Figure 7 shows these curves grouped together on one page. At any one fatigue life shown here, there is not more than 1000 psi. difference in fatigue strength between the curves representing the various sheets of material.

A recent report by the Batelle Memorial Institute[11] gives values of fatigue strength versus fatigue life for .032 inch 24S-T aluminum alloy sheet with the bending stress applied parallel to the direction of rolling. If these values are plotted on Figure 7 the curve will fall on top of the curve for the .032 inch sheet from the tests of this investigation except for the larger values of fatigue life (10^7 cycles) where the Battelle curve is approximately 1000 psi. lower.

It would perhaps be more logical to plot each curve as a band which includes the scatter of the data. This method is not incorporated here owing to the practical difficulties involved. If the data were presented in this manner it is seen that there would be an overlap of the curves in all cases to the extent that the variation in fatigue strength from curve to curve at any one fatigue life could very well be said to be negligible.

The curves of Figure 7 do not fall in the sequence according to their thickness as one would expect. The .040 inch thick sheet

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[11] Jackson, L. R., Grover, H. J., and McMaster, R. C., Advisory Report on Fatigue Properties of Aircraft Materials and Structures, OSRD No. 6600, Serial No. M-653 March 1, 1946 pp. 43

shows a lower fatigue life than the other sizes for the entire range of fatigue life considered herein. However, on referring to the table of physical properties of the various sheets tested, as given in Table I of Appendix II it is seen that the physical properties of the .040 inch sheet are only slightly higher than those of the .032 inch sheet, but much lower than those of .064 and .072.

A recent report by the Battelle Memorial Institute[12] has included the curve of Figure 13 which shows the rather meager data obtainable on the variation of fatigue strength with variation of ultimate strength. In effect, the curve shows the general trend but it probably should not be used to correct sets of data to the same ultimate strength. This data was recorded at a fatigue life of 5×10^8 cycles and its application to correcting data of shorter life cycles is perhaps questionable. It does seem reasonable to assume that an increase in ultimate strength means generally an increase in the fatigue strength of 24S-T aluminum alloy. This has been shown to be true for other metals. Referring again to Table I it is seen that the yield and ultimate stress increase with the size of the material although there is a very small increase in strength from the .032 inch thick sheet to the .040 inch thick sheet. Figure 7 shows a decrease in fatigue strength from the .032 inch to the .064 inch, .072 inch and .040 inch thick sheet. These trends then indicate that while the increase in ultimate strength with thickness

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12 <u>Ibid</u>., pp. 61, Battelle Report.

tends to increase the fatigue strength, the curves show a decrease in fatigue strength due to increase in thickness, sufficient to offset the first mentioned effect. This deduction is borne out again on noting the increased fatigue strength spacing of the curves of the .032 inch and the .040 inch thick sheets. There is very little increase in fatigue strength due to variations of ultimate strength in these two sheets and hence the decrease in fatigue strength due to the increase in thickness from .032 inch to .040 inch has a relatively greater effect in lowering the fatigue strength curve of the .040 inch thick sheet. The .064 and .072 inch sheet again bears out this reasoning in that while their ultimate strengths differ by 3000 psi., the size effect almost eliminates the spacing between the curves.

It is evident that in order to make a comparison of the fatigue strength of the various sheets, the curves should first be corrected for ultimate or yield stress difference. It was noted that the yield point variation from sheet to sheet was roughly porportional to the ultimate strength variation from sheet to sheet. It is believed that the correction according to yield point would be more logical, as will be further discussed, but since other investigators[13] have used the ultimate strength as a basis, also since it is roughly porportional to the yield point, the adjustments are made on this basis. Figure 8 of the Appendix shows the

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[13] Ibid., Battelle Report, pp. 61

curves of Figure 7 adjusted by the ratio of ultimate stress of the sheet in question to the ultimate stress of .072 inch thick sheet. The curves plotted in this manner show a small decrease of fatigue strength with increase of thickness of the sheet. v. Philipp specifies that on decreasing the size of sheet tested the fatigue strength will increase and reach a maximum at a thickness of 6 mm. after which the deviation cannot be attributed to size effect. It must be realized that v. Philipp is speaking of rather large deviations. For example, Buchmann[14] specified that the flexural fatigue strength of a rod 100 mm. in diameter is 60 % of that of a rod 15 mm. in diameter. The decrease in fatigue strength with increase of size as shown on Figure 7 is so small that the scatter of the data for any one curve would almost encompass the spread of the curves as shown plotted on Figure 7. Hence with the data plotted in this manner, the conclusion is that yield point or ultimate strength variation causes more change of fatigue strength than does the change due to variation of the sheet thickness in the range of sizes considered in this investigation.

Figure 9 shows the data plotted as the ratio of fatigue strength to ultimate strength versus fatigue life. The Battelle[15] Report uses a ratio of stress amplitude to static ultimate versus

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14 Buchmann, W., "Influence of Cross-Sectional Area on Fatigue Strength," Engineer's Digest, March 1945

15 Ibid., Battelle Memorial Institute Report, pp. 54

the ratio of mean stress to static ultimate to determine the effect of mean stress on range of load for four aluminum alloys. When the curve sheet of the Battelle Report is examined it is apparent that the curves apply to all of the four alloys and that it was not necessary to plot individual curves for each alloy. In the case of fully reversed flexure, the stress amplitude is equal to the fatigue strength and of course the mean stress is zero. If this procedure of using the ratio of fatigue stress to ultimate stress is applicable to different aluminum alloys it certainly may be applied to different sheets of the same alloy.

The curves as plotted on Figure 9 show that there is a small decrease in the ratio of fatigue strength to ultimate strength with increases in the thickness of the sheet considered. This method of presenting the results is perhaps the one which will be most useful, as the use of the dimensionless coefficient, the ratio of fatigue strength to ultimate strength allows for a more universal comparison of data.

CONCLUSIONS

From the foregoing presentation of the results of this investigation the following conclusions are drawn:

1. The effect of thickness on fatigue strength is small in the range of sizes tested.

2. The variation of yield point strength or ultimate strength in 24S-T3 material has a greater effect on the fatigue strength than the variation in thickness.

3. v. Philipp's statement that the upper limit of flexural fatigue strength is reached with a height of specimen of 6 mm. was tested for the range of .8 to 2 mm. The tests show a small decrease in fatigue strength with increase in size. Therefore, the simplified stress distribution does not exactly fit the true case for thin specimens.

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APPENDIX I

An explanation of the method used by v. Philipp in deriving formulae for the computation of Flexural and Torsional Fatigue Strength in terms of Alternating Fatigue Strength is included herein.

Stress Distribution Assumed

v. Philipp has assumed a distribution of bending stress over the cross section as shown in Figure 2 of Appendix III. This is of course a simplified distribution, assumed for the purpose of allowing a mathematical derivation of formulae which enables the predicting of flexural or torsional fatigue having given the alternating tension fatigue data.

Basis for the Assumed Stress Distribution

It has been noted that the flexural fatigue strength for thick members approaches the alternating tension fatigue strength as an asymptote when the variable of size is increased. (see Figures 10 and 11.) However, when the thickness is decreased, the flexural fatigue strength increases while the alternating tension fatigue strength remains constant. At any one thickness less than the asymptotic value, the difference of fatigue strength between the flexural and alternating tension fatigue curves for various materials is the same. This phenomenon gives rise to the hypothesis that the deviations from the elastic stress distribution lie in a layer at the surface which is termed the stabilized layer. This has recently been substantiated by X-ray investigations. v. Philipp assumed that the depth of the stabilized layer was a constant, depending on the cross sectional shape of the material and type of loading. He also assumed that the stress is constant in the stabilized layer. If the thickness is decreased so that the stabilized layer becomes porportionately large as compared to the total height of the specimen, the stress distribution approached is that of the thin specimen of

Figure 2 of Appendix III. This type of distribution represents the maximum increase or upper limit of flexural fatigue strength over that of alternating tension fatigue strength because it represents the maximum deviation of the stress distribution for the $\frac{M}{I}y$ distribution ordinarily assumed in computing bending stress.

Derivation of Upper Limit of Flexural Fatigue Strength

For this case v. Philipp has derived the relation between maximum flexural fatigue strength and alternating tension as follows:

From the thin specimen of Figure 2 of Appendix III

$$\sigma b_w = \sigma b_{w\,max} \frac{\frac{h}{2}}{\frac{h_a}{2}}$$

when $\frac{h}{2}$ = distance from neutral axis to point in question

$\frac{h_a}{2}$ = distance from neutral axis to outer fiber

With cross section width b variable at will over the cross section height, the following holds true:

$$M_{b\,max} = 2\int_{\frac{h}{2}=0}^{\frac{h}{2}=\frac{h_a}{2}} \sigma z_w \, b \, \frac{h}{2} \, d\left(\frac{h}{2}\right) = 2\int_{\frac{h}{2}=0}^{\frac{h}{2}=\frac{h_a}{2}} \sigma b_w \, b \, \frac{h}{2} \, d\left(\frac{h}{2}\right)$$

or if we substitute b_w according to the above equation

$$\sigma z_w \int_0^{\frac{h_a}{2}} b \frac{h}{2} d\left(\frac{h}{2}\right) = \sigma b_{w\,max} \frac{2}{h_a} \int_0^{\frac{h_a}{2}} b\left(\frac{h}{2}\right)^2 d\left(\frac{h}{2}\right)$$

From this we may calculate $\sigma b_{w\,max}$ by correspondingly expressing **b** in the cross section form.

For a **flat bar:**

with b = b_a = a constant, the investigation gives

$$\sigma z_w \left[b_a \frac{\left(\frac{h}{2}\right)^2}{2} \right]_0^{\frac{h_a}{2}} = \sigma b_{w\,max} \frac{2}{h_a} \left[b_a \frac{\left(\frac{h}{2}\right)^3}{3} \right]_0^{\frac{h_a}{2}}$$

$$\sigma z_w \left[b_a \frac{h_a^{\,2}}{8} \right] = \sigma b_{w\,max} \frac{2}{h_a} \left[b_a \frac{\frac{h_a^{\,3}}{8}}{3} \right]$$

$$\frac{3}{2} \sigma z_w = \sigma b_{w\,max}$$

which shows that the upper limit of flexural fatigue strength should be equal to $1\frac{1}{2}$ times the alternating tension endurance limit for specimens of rectangular cross section which are thin enough to allow the assumed stress distribution to be approximated.

APPENDIX II, Tables

TABLE I

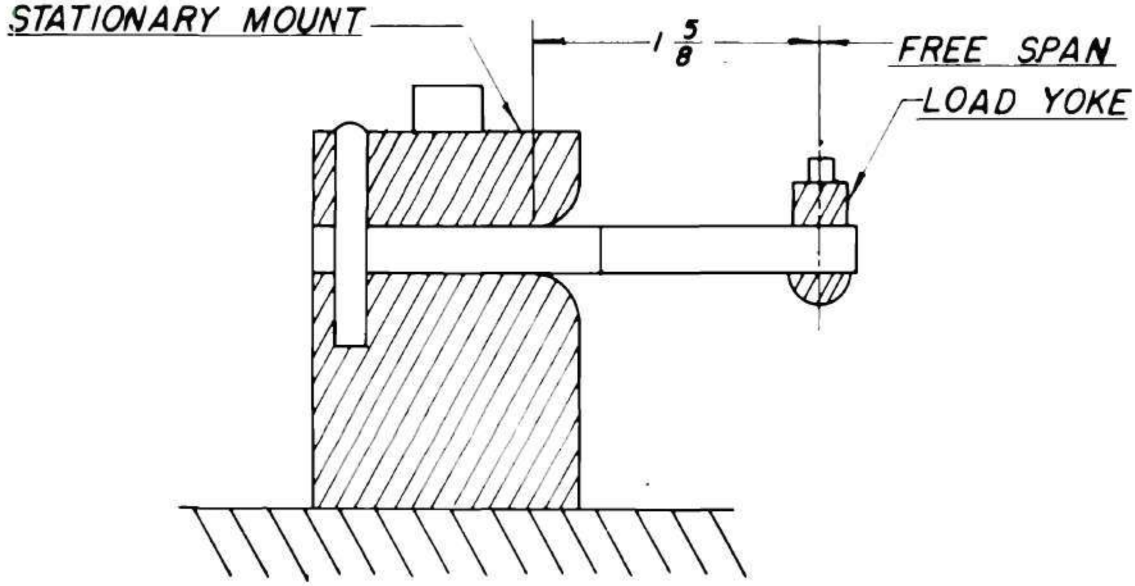
MECHANICAL PROPERTIES OF 24S-T3 SHEETS

USED IN FATIGUE TESTS

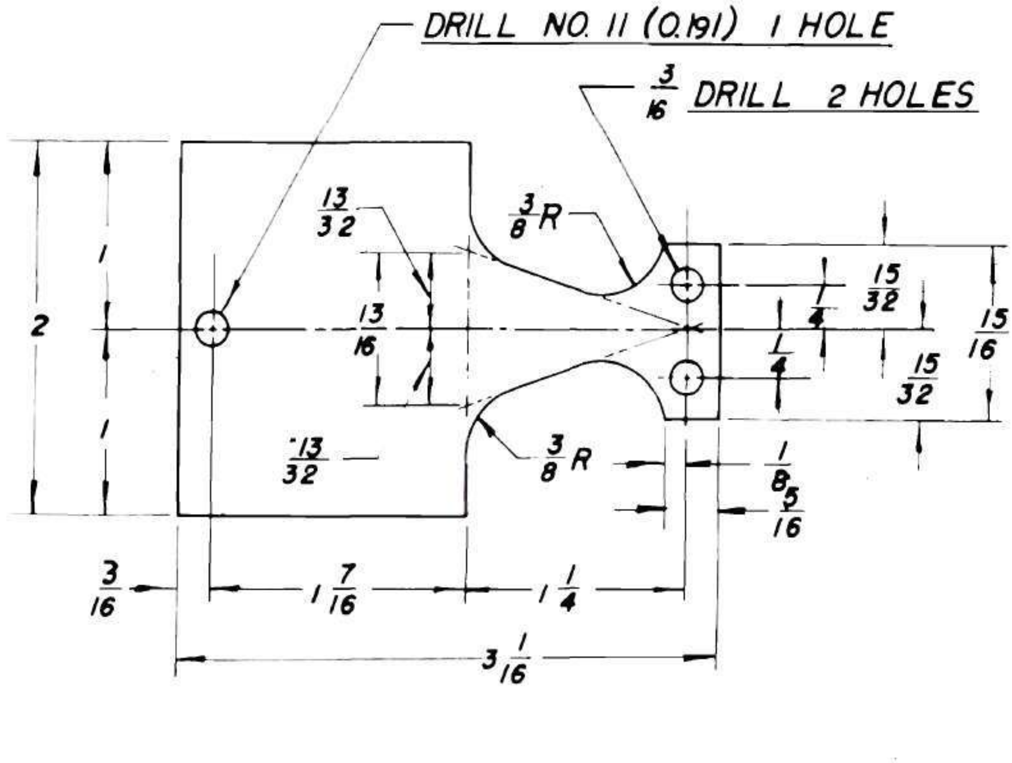
SHEET THICKNESS INCHES	E, MODULUS OF ELASTICITY PSI	YIELD STRENGTH PSI	ULTIMATE STRENGTH PSI
.032	10.2×10^6	51,000	66,700
.040	10.2×10^6	51,400	67,600
.064	10.2×10^6	52,400	68,500
.072	10.2×10^6	55,650	71,500

APPENDIX III, Figures

FIGURE I
SPECIMEN AND MOUNTING DETAILS



CROSS SECTIONAL VIEW OF SPECIMEN MOUNTING

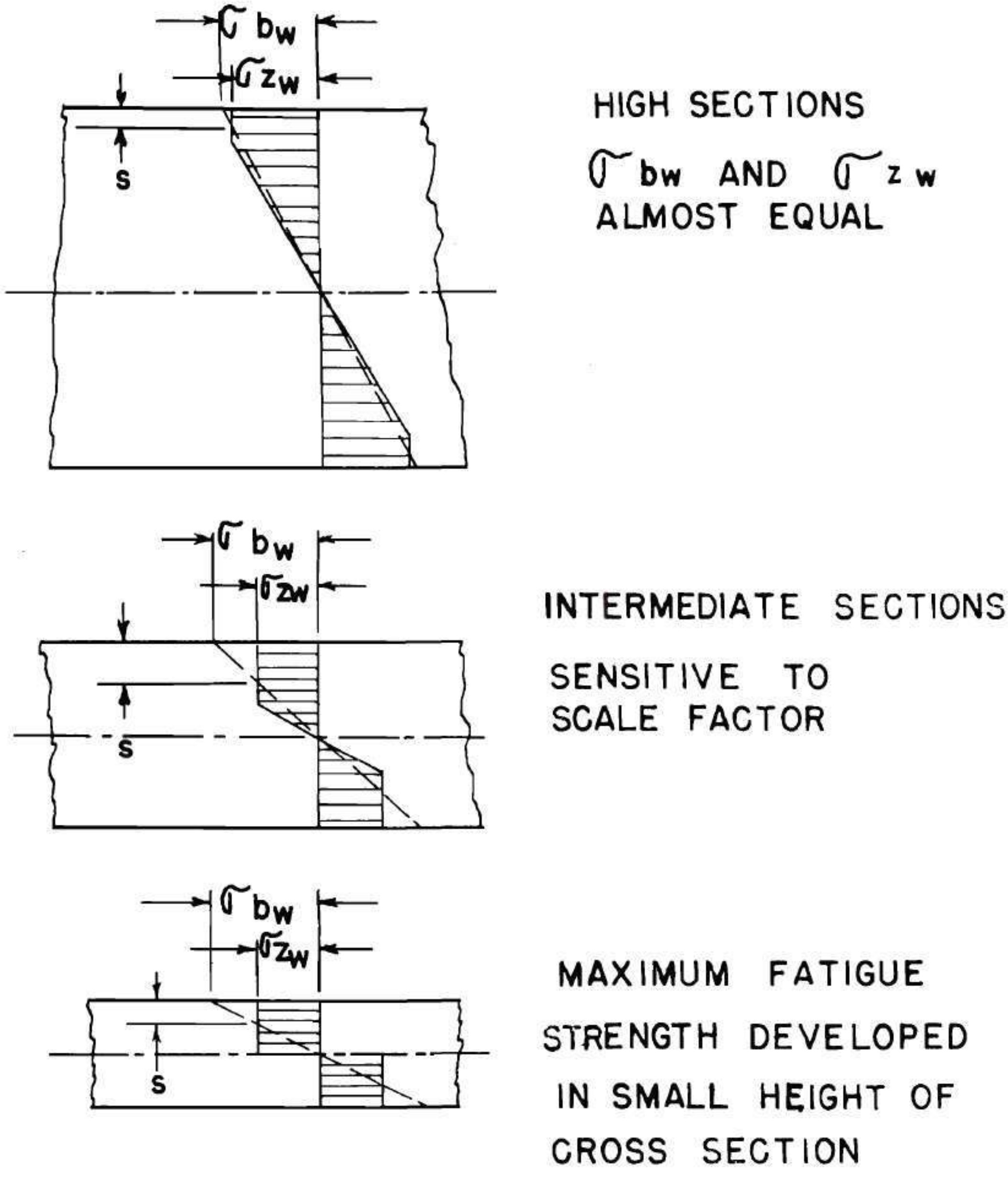


SPECIMEN DETAILS

ALL DIMENSIONS IN INCHES

FIGURE 2

SIMPLIFIED STRESS DISTRIBUTION ASSUMED BY v. PHILIPP FOR FLEXURAL FATIGUE



σ_{bw} = FATIGUE STRENGTH IN REVERSED FLEXURE

σ_{zw} = FATIGUE STRENGTH IN REVERSED AXIAL LOAD

S = HEIGHT OF STABILIZED LAYER

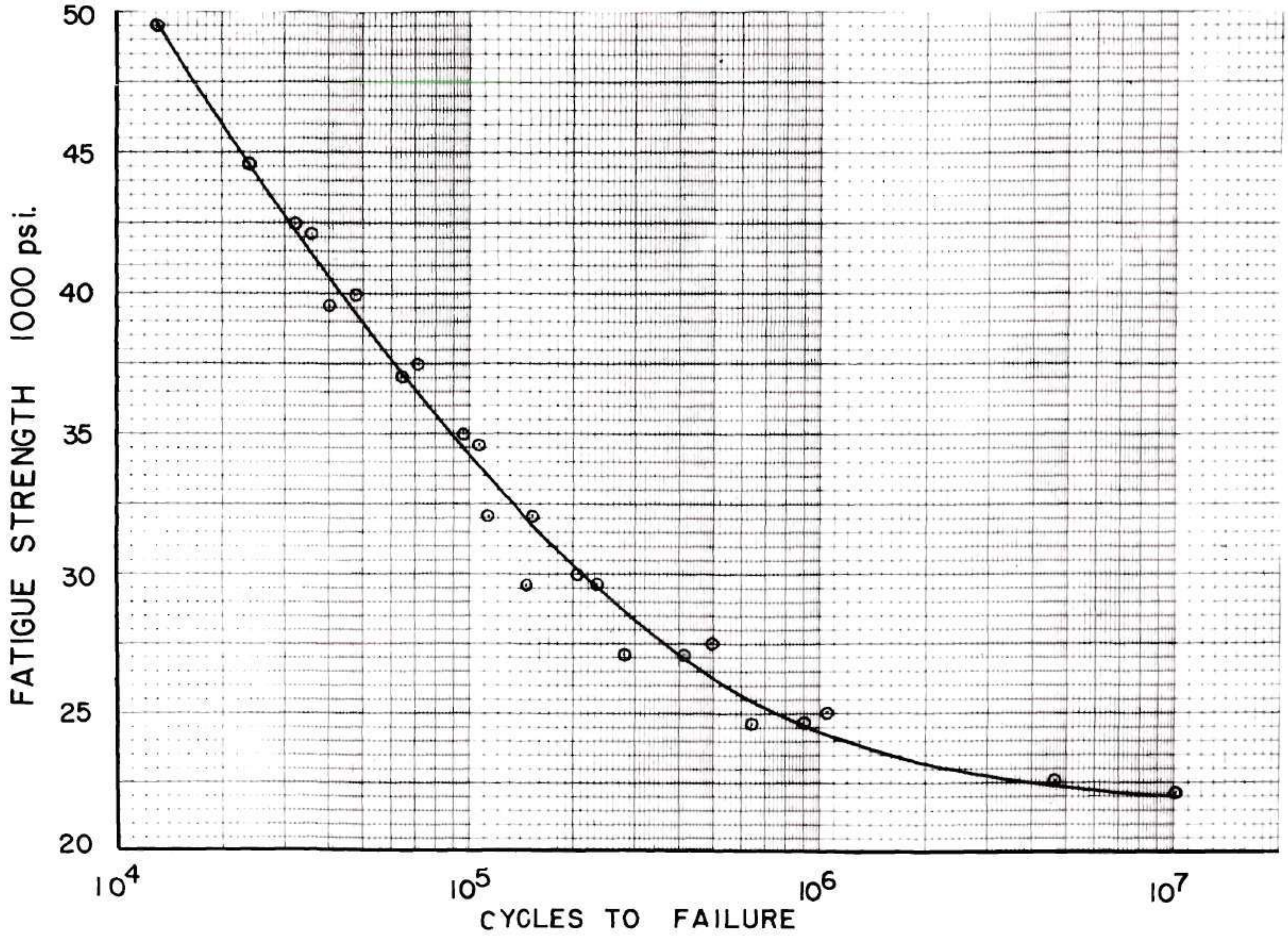


FIGURE 3. FATIGUE TEST RESULTS FOR POLISHED .032 24S-T3 SHEET

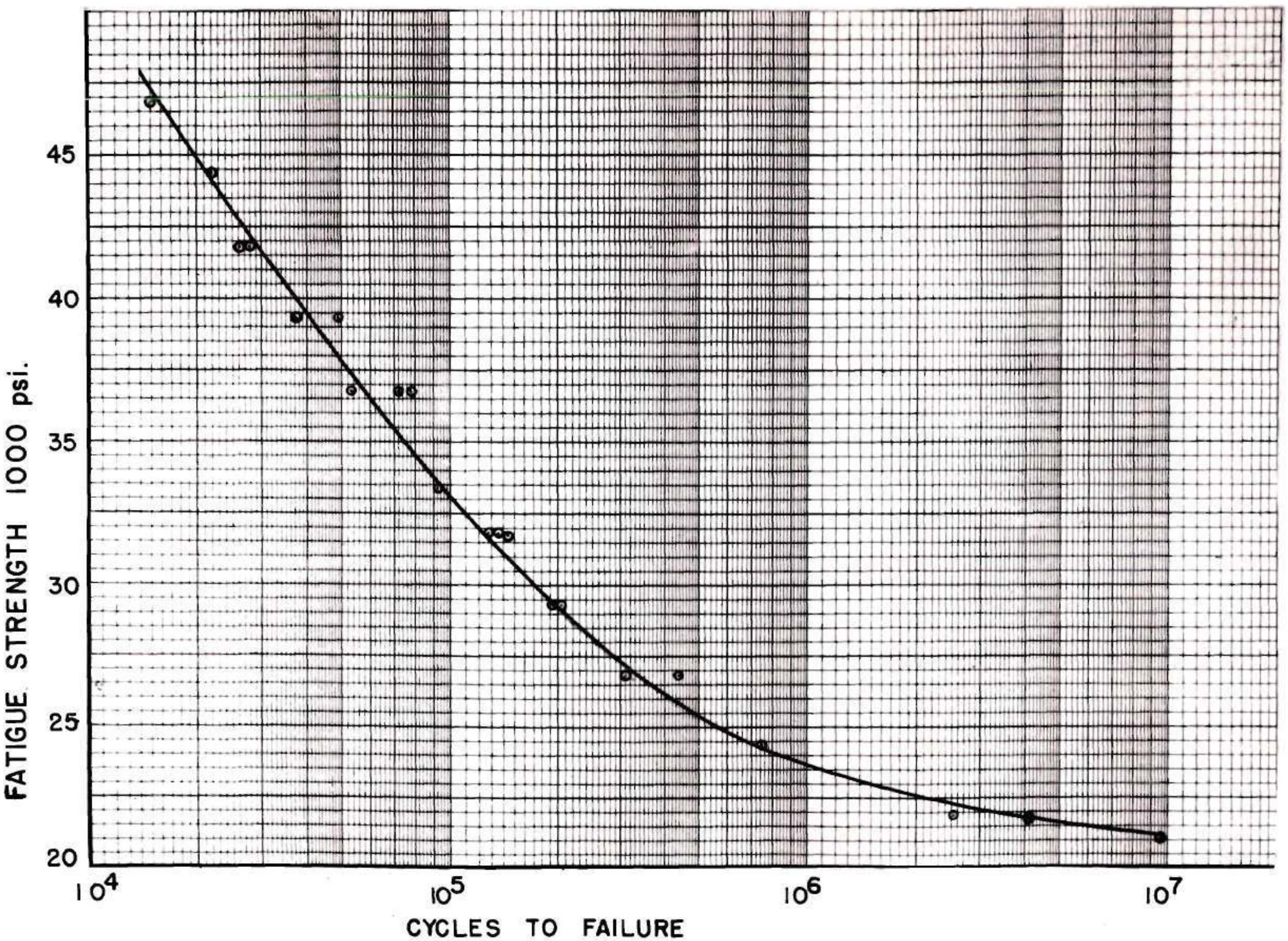


FIGURE 4. FATIGUE TEST RESULTS FOR POLISHED .040 24S-T3 SHEET

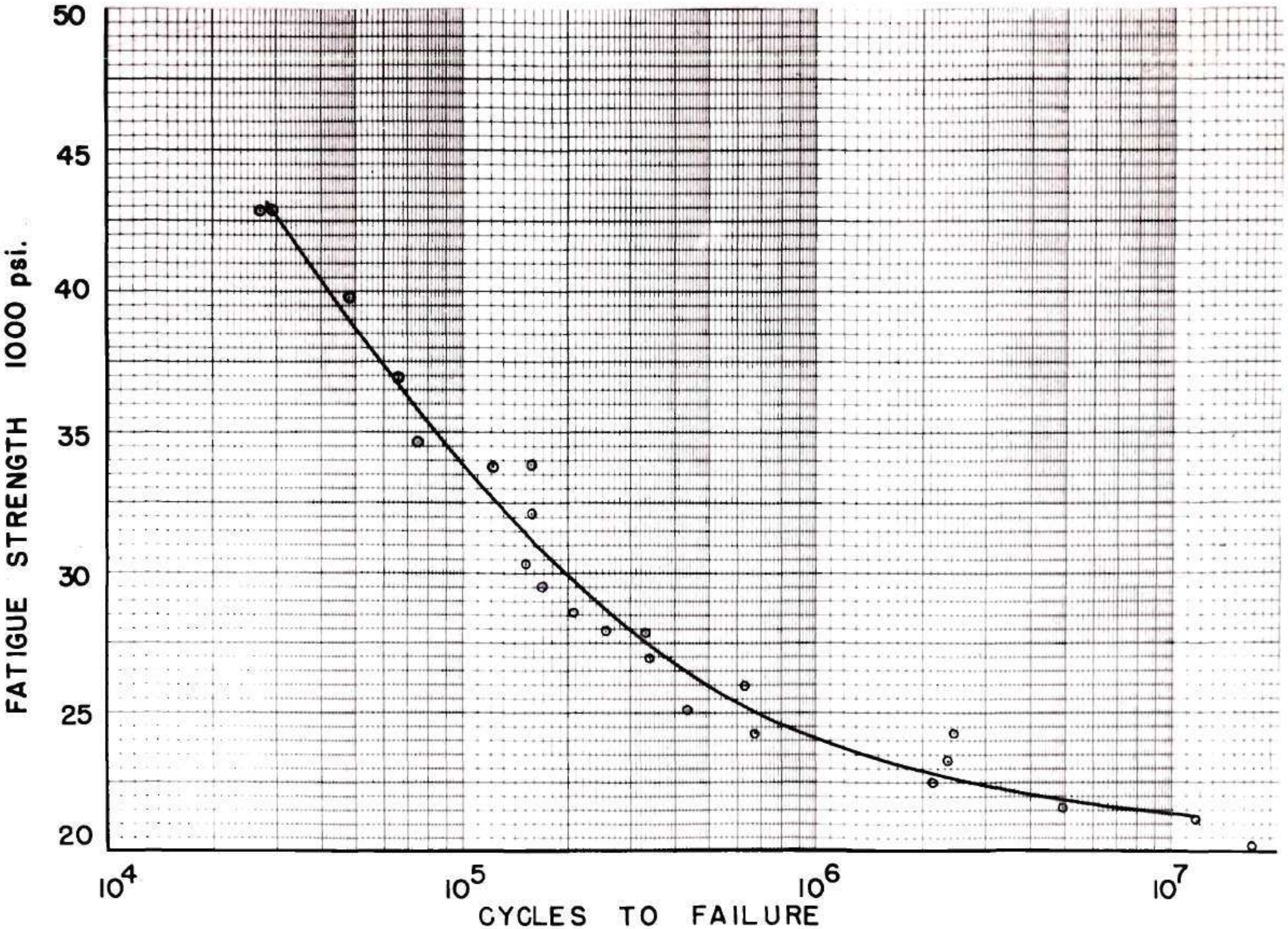


FIGURE 5. FATIGUE TEST RESULTS FOR POLISHED .064 24S-T3 SHEET

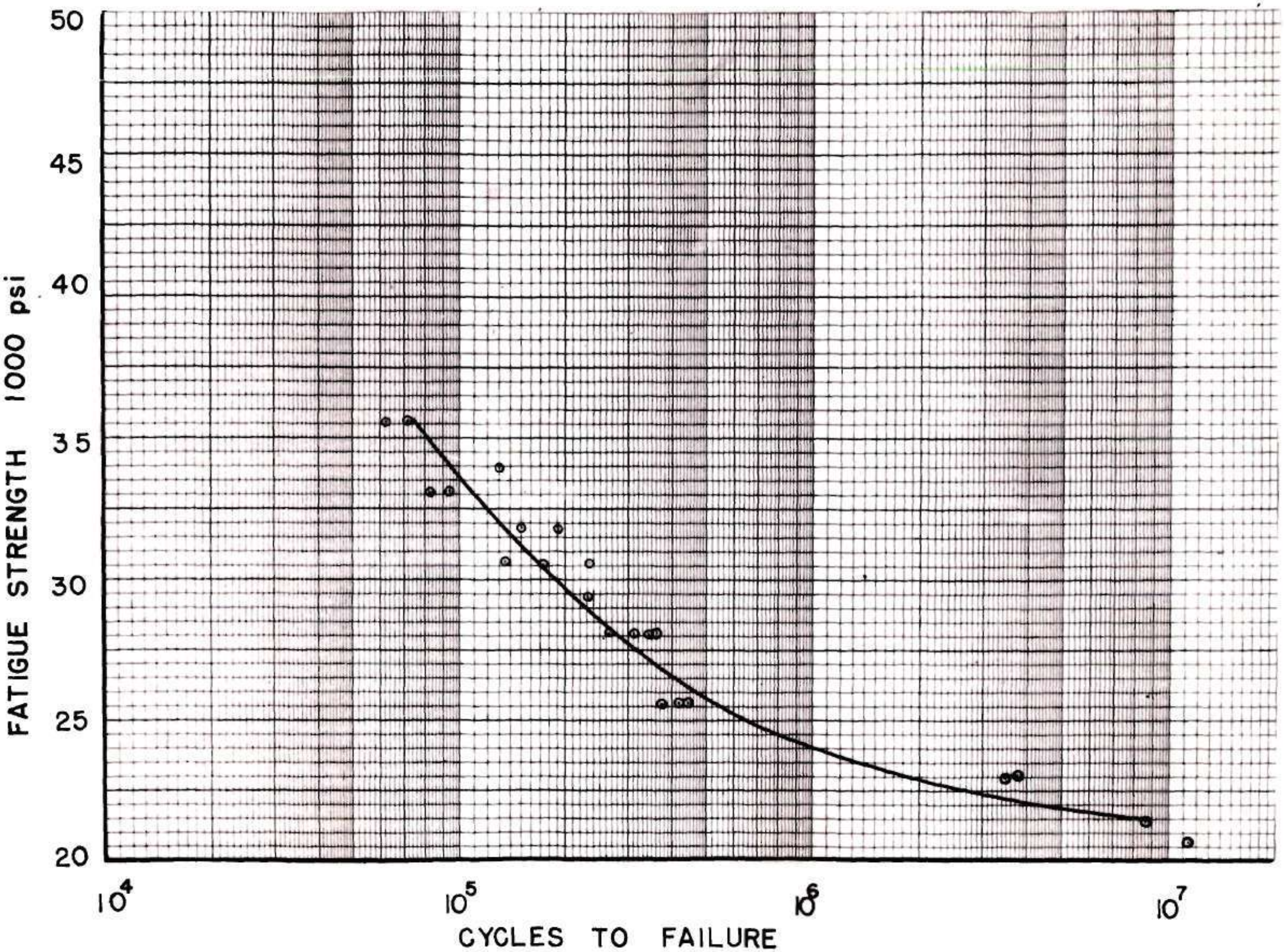


FIGURE 6. FATIGUE TEST RESULTS FOR POLISHED .072 24S-T3 SHEET

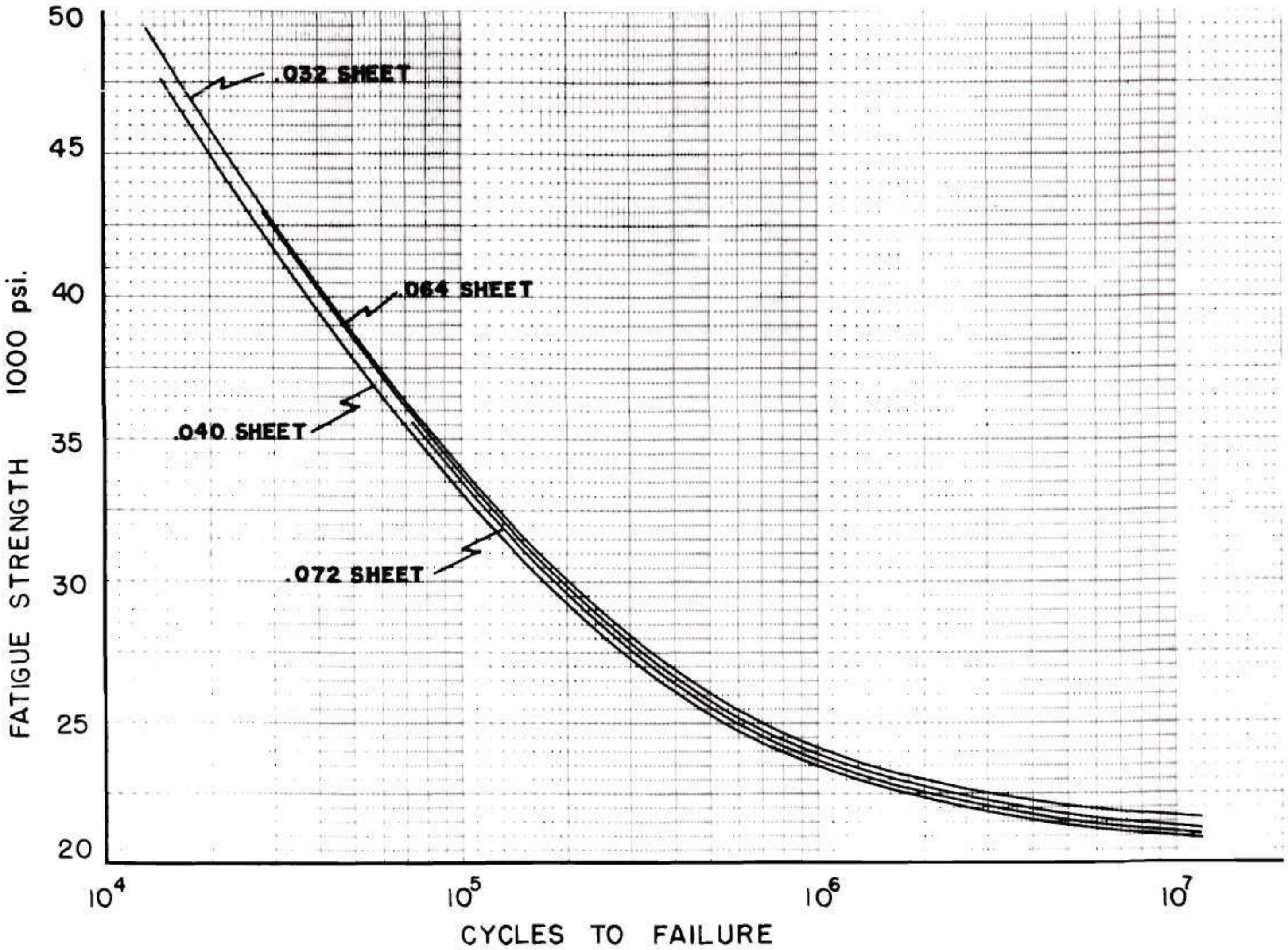


FIGURE 7. COMPARISON OF FATIGUE TEST RESULTS FOR POLISHED .032, .040, .064 AND .072 in. 24S-T3 SHEET

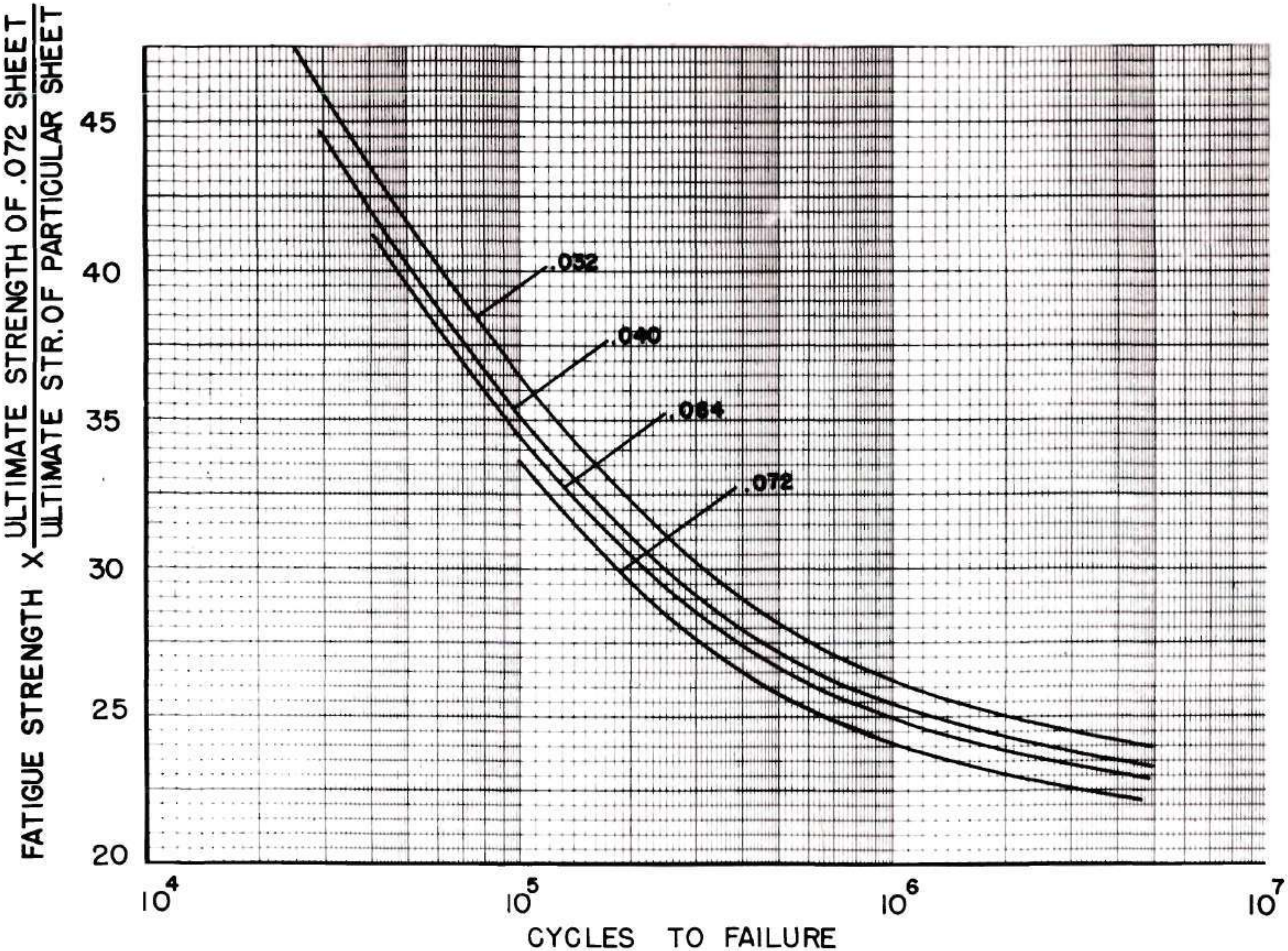


FIGURE 8. FATIGUE TEST RESULTS MODIFIED BY RATIO OF ULTIMATE STRENGTHS

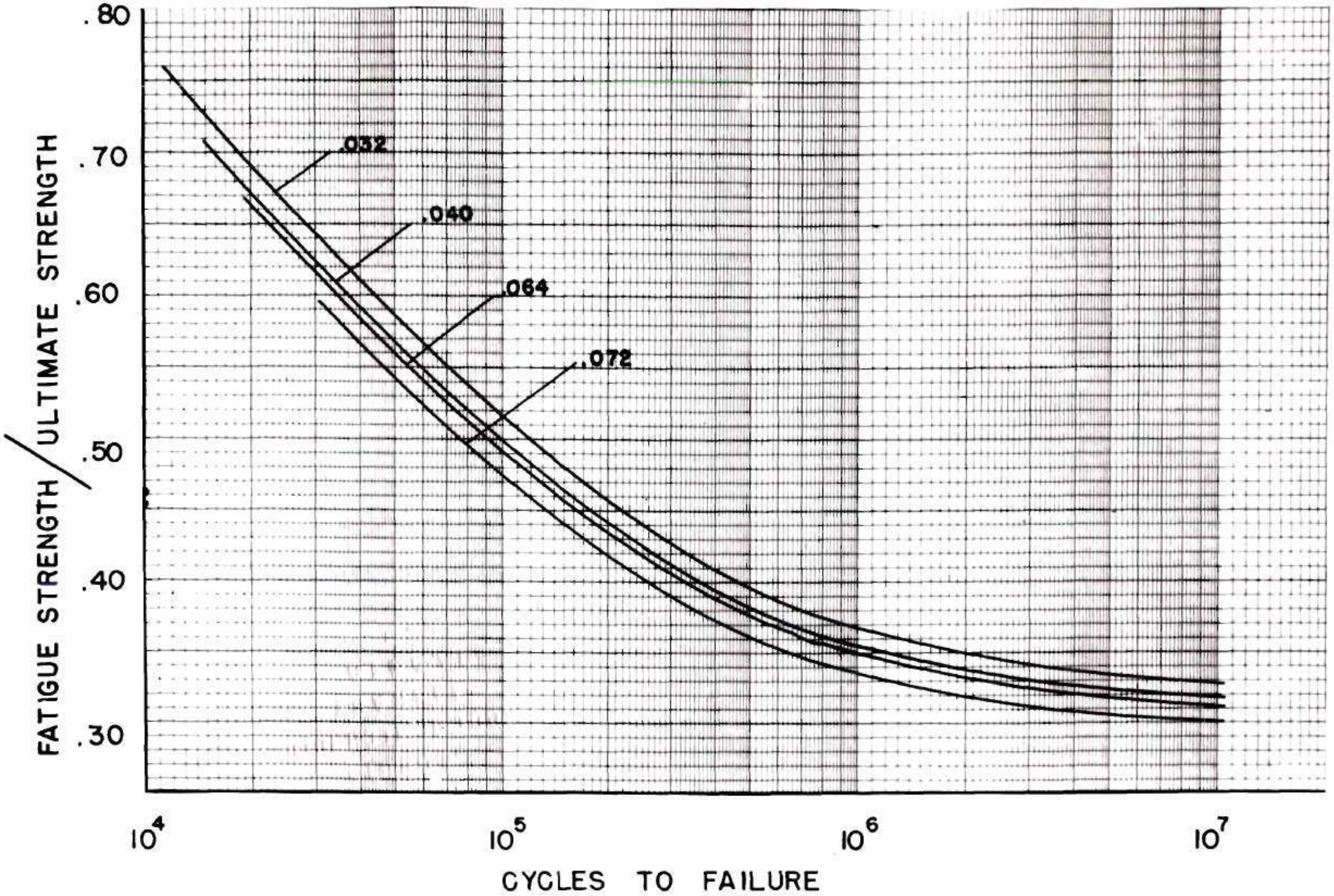
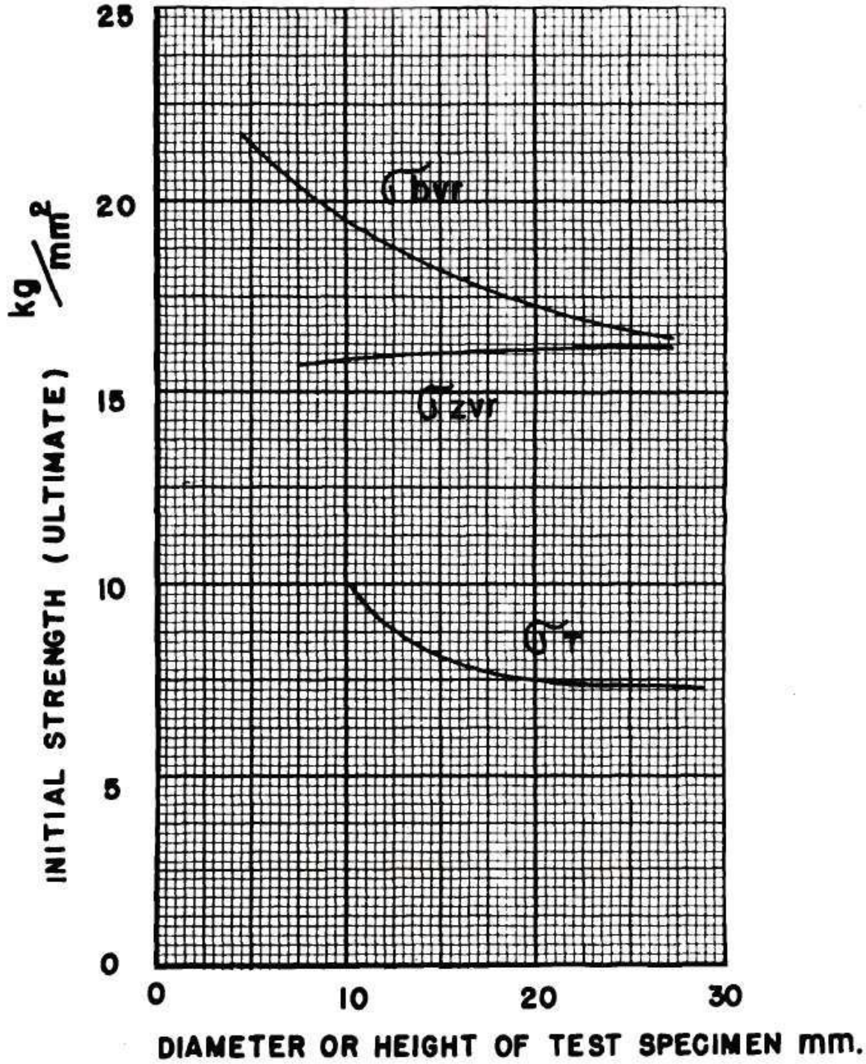


FIGURE 9. RATIO OF FATIGUE STRENGTH TO ULTIMATE STRENGTH VERSUS FATIGUE LIFE FOR FOUR SIZES OF SHEET

FIGURE 10.



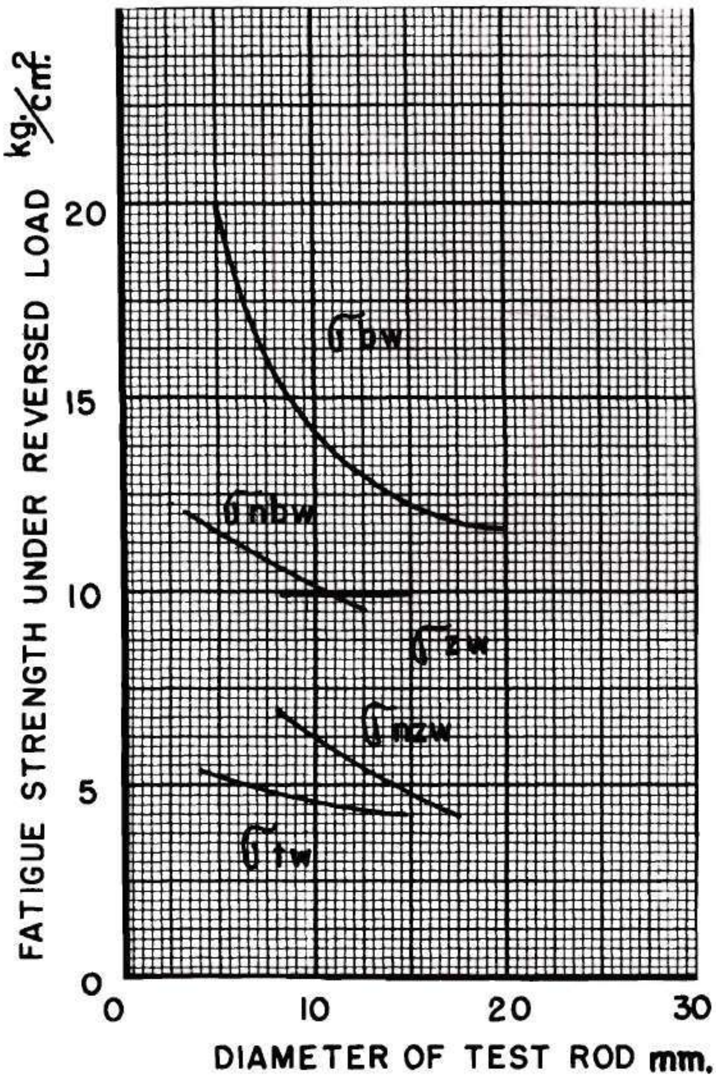
COMPARISON OF ULTIMATE FLEXURE, TENSILE AND TORSIONAL STRENGTH
BY W. BUCHMANN

σ_{bvr} = ULTIMATE FLEXURAL STRENGTH

σ_{zvr} = ULTIMATE TENSILE STRENGTH

σ_{t} = ULTIMATE TORSIONAL STRENGTH

FIGURE 11.



EFFECT OF SCALE FACTOR FOR ELEKTRON AZM

σ_{bw} = REVERSED FLEXURAL FATIGUE

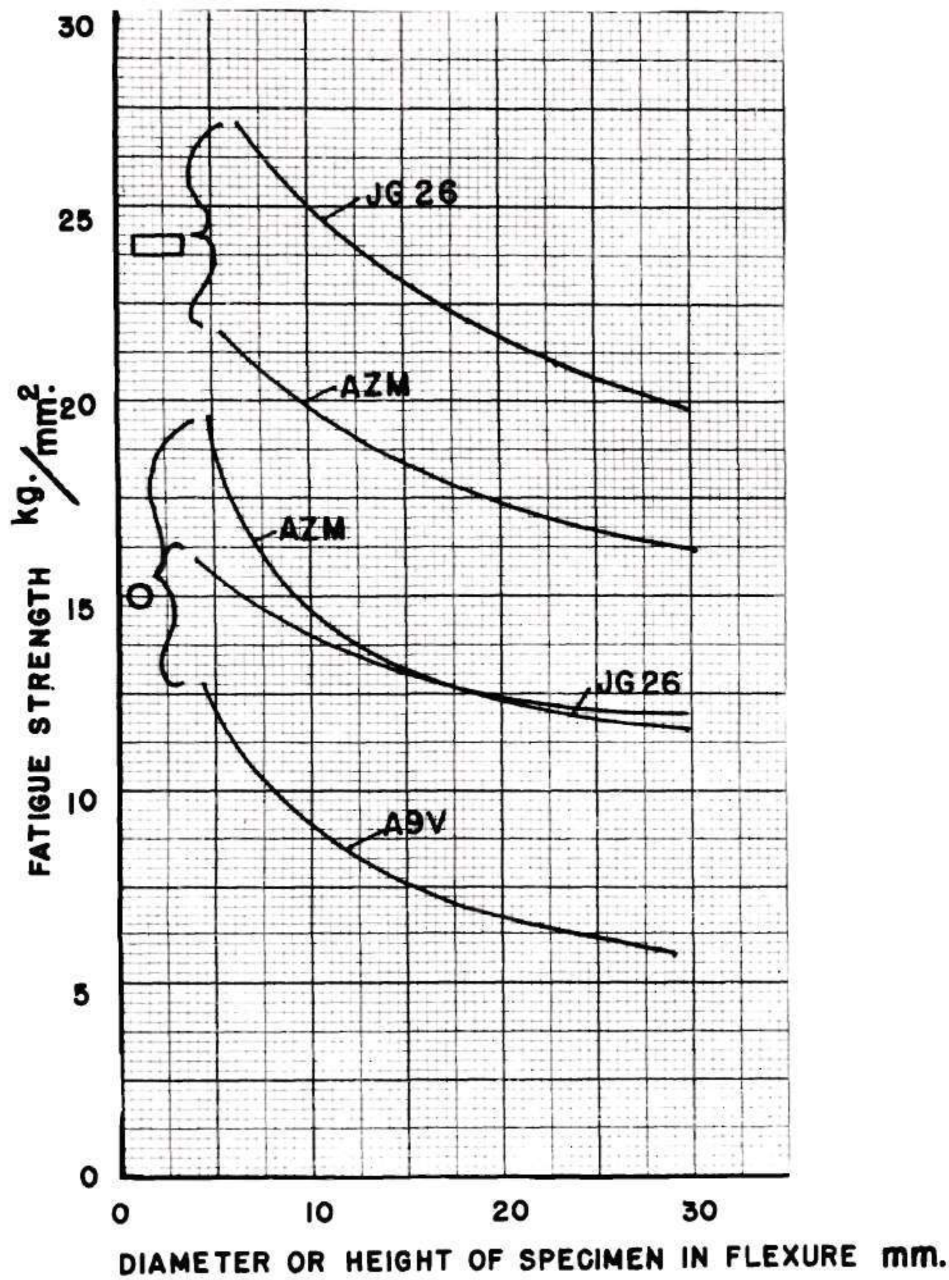
σ_{zw} = REVERSED AXIAL LOAD FATIGUE

σ_{tw} = REVERSED TORSIONAL FATIGUE

σ_{nbw} = REVERSED FLEXURAL FATIGUE-NOTCHED

σ_{nzw} = REVERSED AXIAL LOAD FATIGUE-NOTCHED

FIGURE 12.



INFLUENCE OF THE CROSS SECTION ON FATIGUE STRENGTH FOR TWO LIGHT ALLOYS

BY

W. BUCHMANN

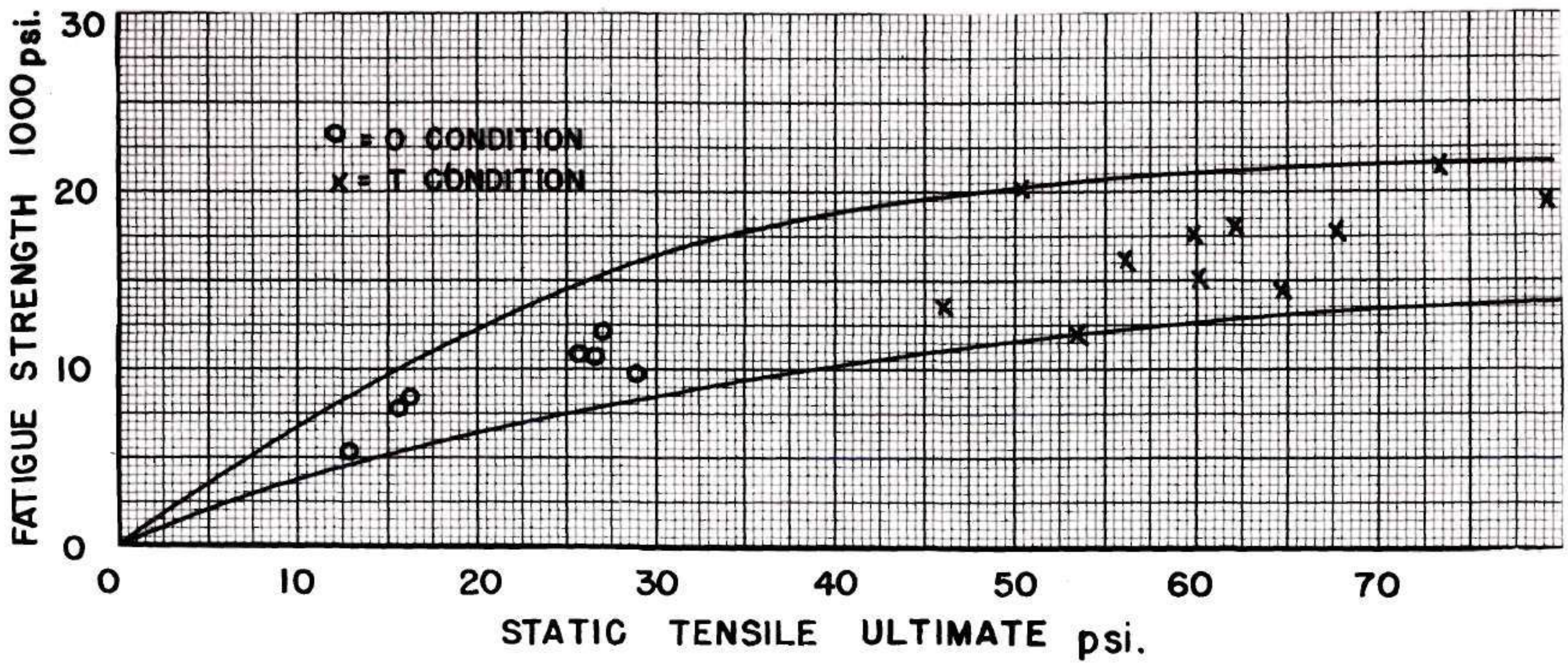


FIGURE 13. ROTATING BEAM FATIGUE STRENGTH AT 5×10^8 CYCLES FOR WROUGHT ALUMINUM ALLOYS

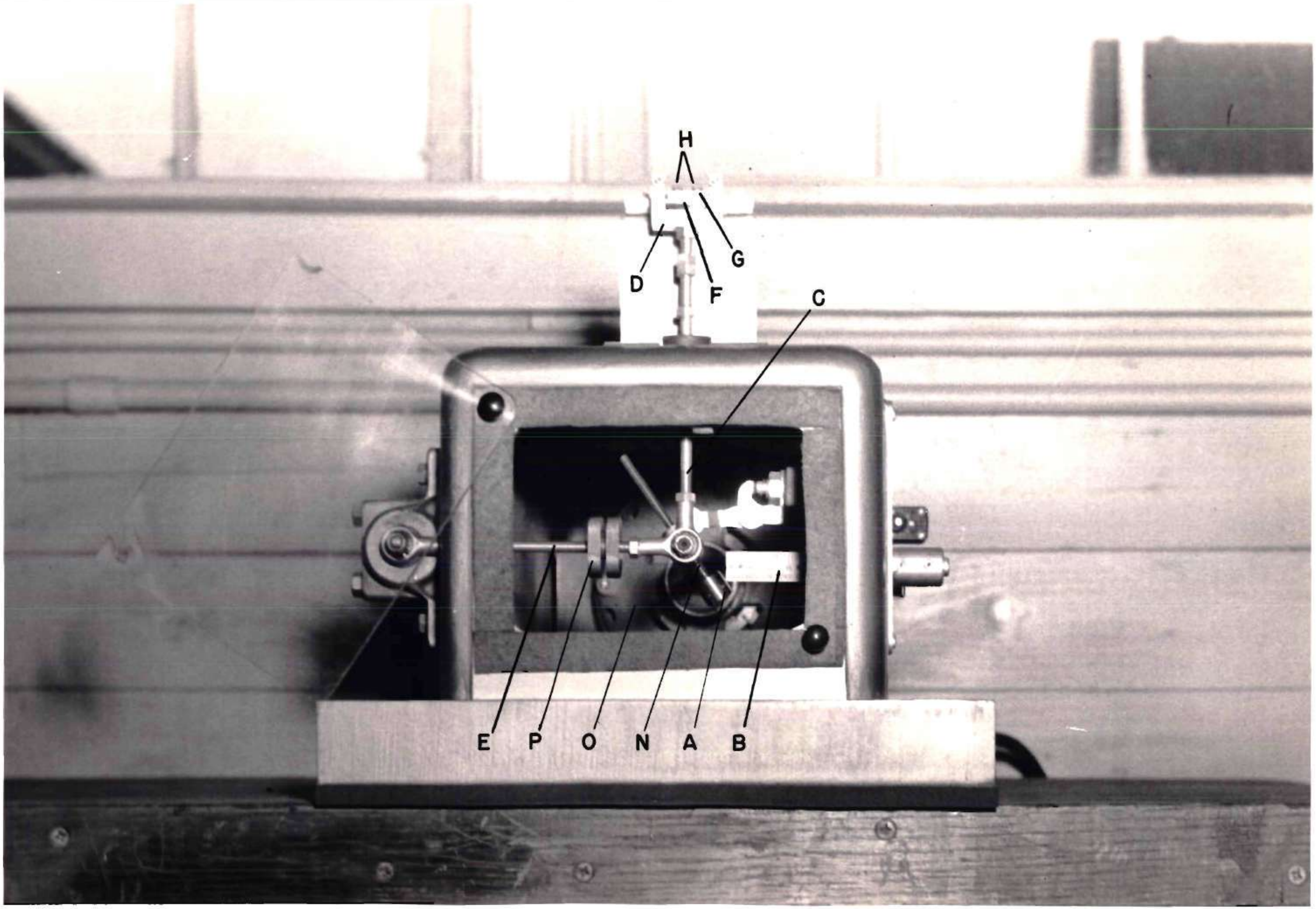


FIGURE 14. SONTAG FLEXURE FATIGUE MACHINE MODEL SF-2

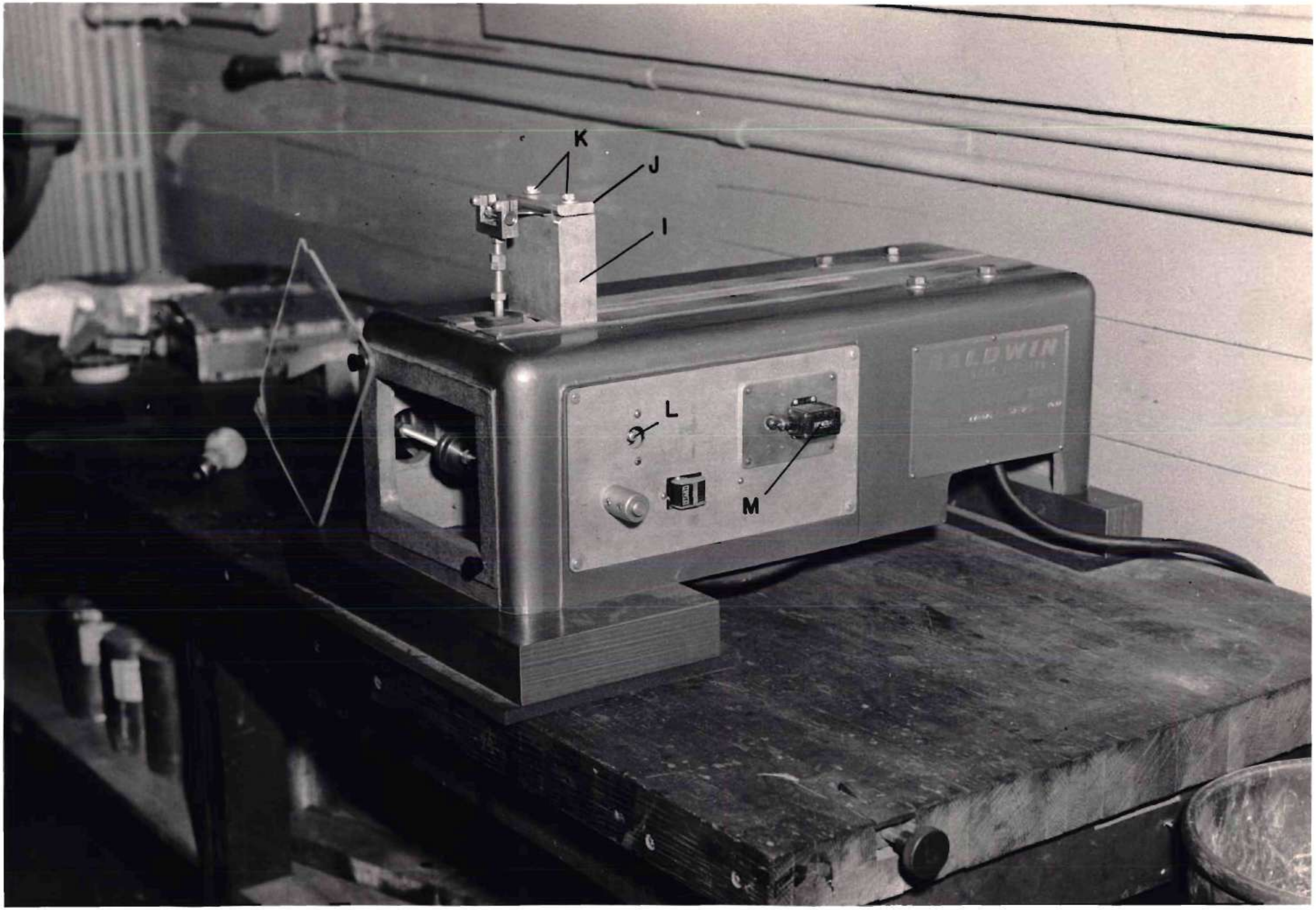


FIGURE 15. SONTAG FLEXURE FATIGUE MACHINE MODEL SF-2

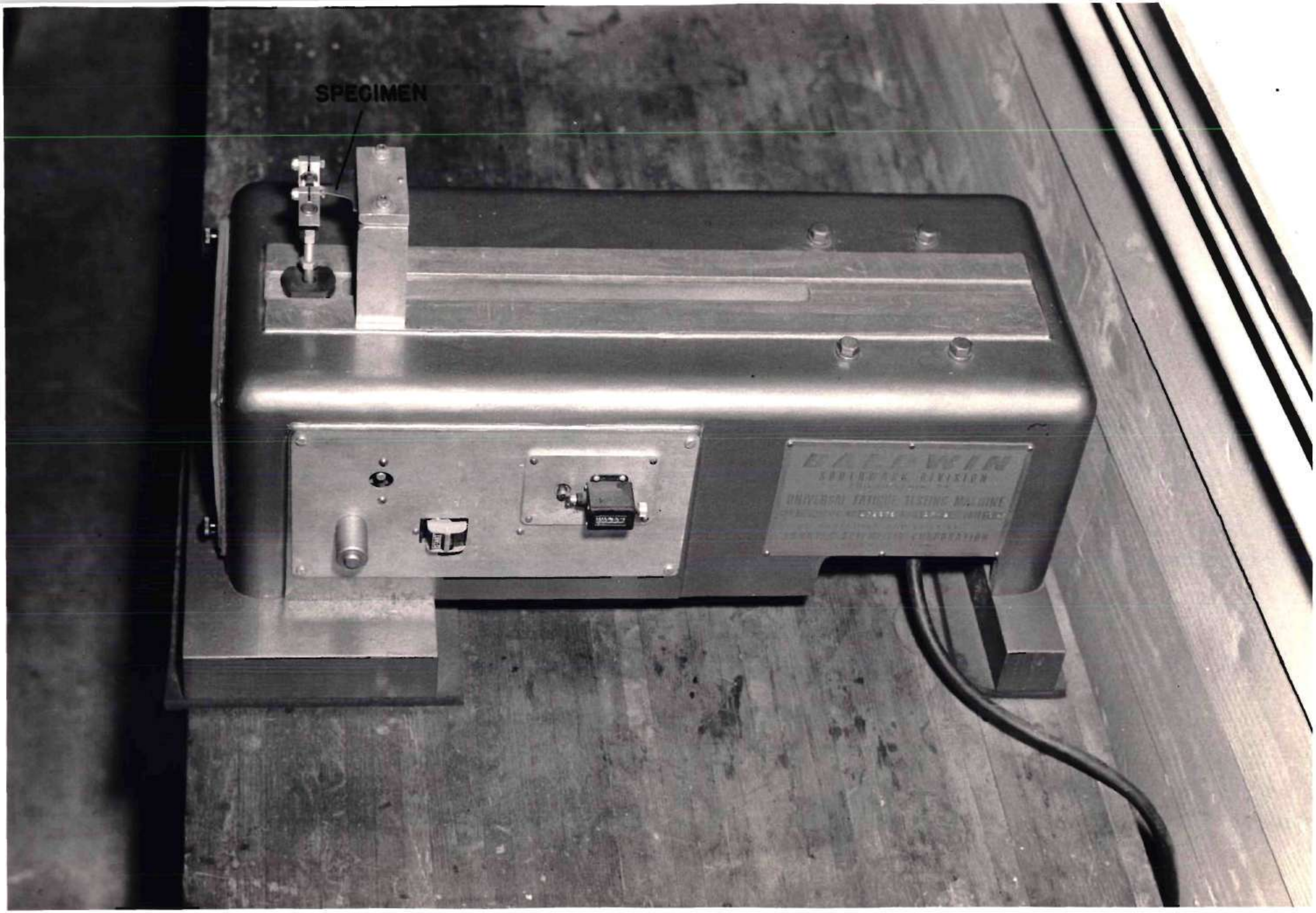


FIGURE 16. SONTAG FLEXURE FATIGUE MACHINE MODEL SF-2

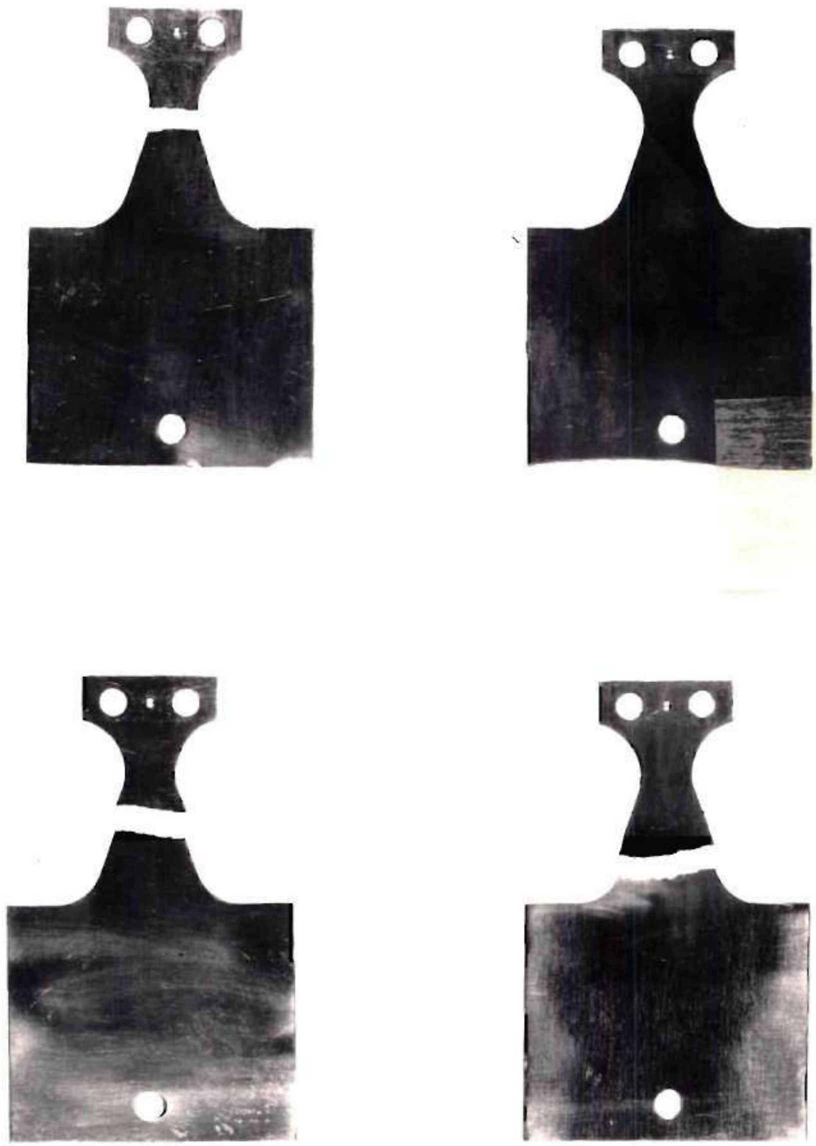


FIGURE 17. PHOTOGRAPH OF SPECIMENS SHOWING RANDOM BREAK

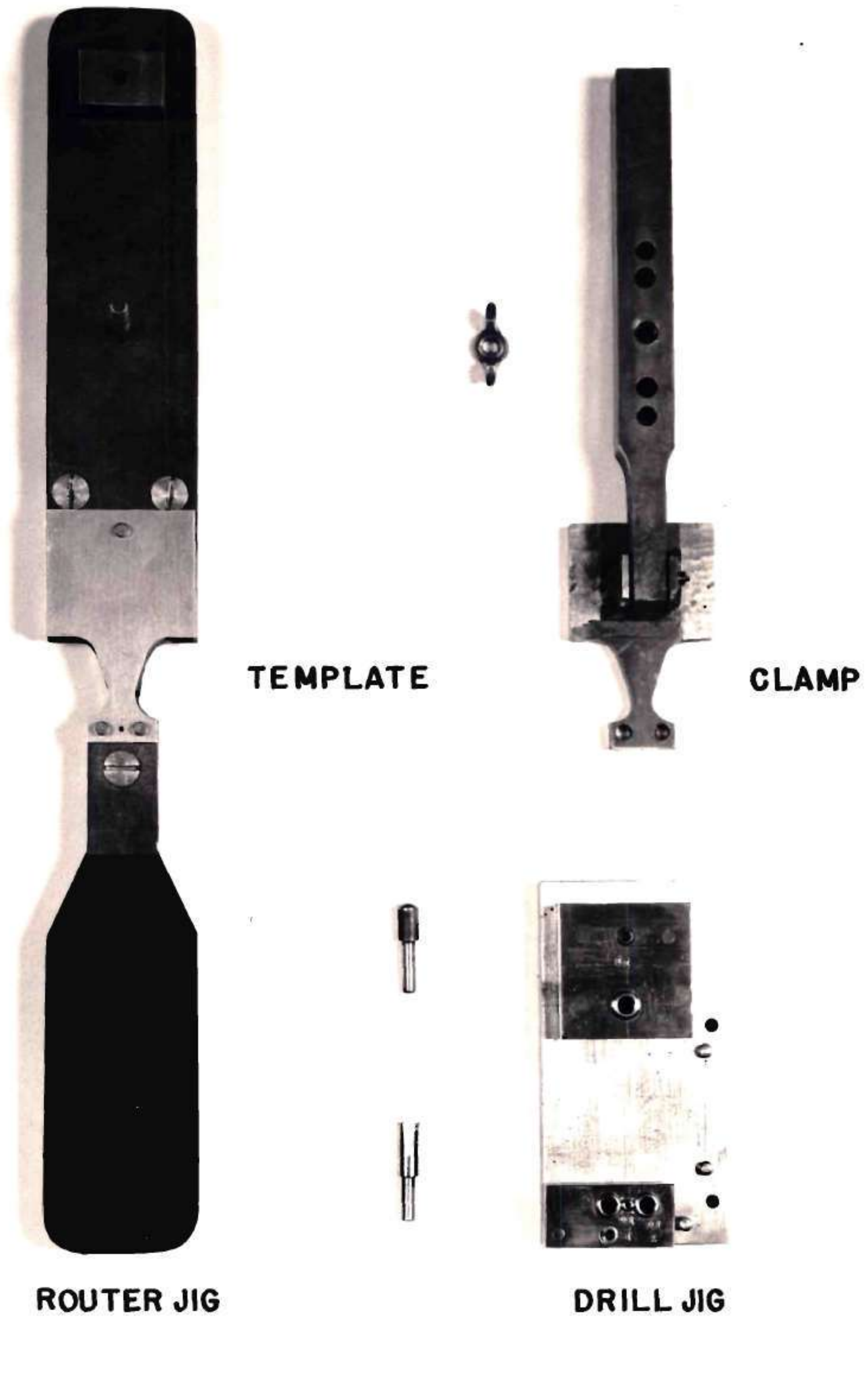


FIGURE 18. PHOTOGRAPH OF DRILL JIG AND ROUTER JIG